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Radioactivity in Drinking Water

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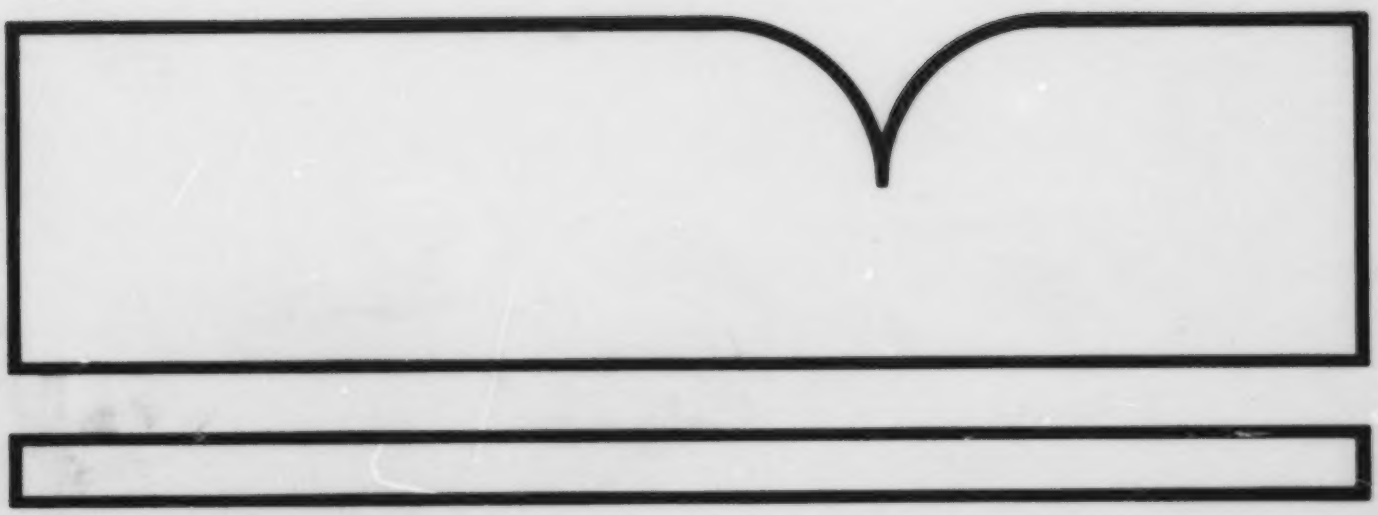

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This general overview is designed to assist those involved with public health and drinking water to better understand, interprete and implement EPA's regulation for radioactivity in drinking water. In this presentation the general nuclear properties are shown using naturally occurring isotopes such as radium, radon and uranium as examples. The units of radioactivity(curie, rad and rem) are explained and demonstrated in describing natural radiation ; in our surroundings and bodies as well as man-made radiation from medical x-rays, TV, fallout, industrial uses and nuclear power plants and other sources. The health effects discussed include birth defects, genetic damage, cancers, leukemias and others. Several specific examples are given in each disease area as well as their relative importance or rate of occurrence. The risk (in deaths/million people exposed/yr) is tabulated for radioactivity and compared to several other cases including disease, accidents and weather.Possible methods for reducing the radioactivity in drinking water are described. Flow charts are provided that show how to interprete the radiation regulations for drinking water.

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RADIOACTIVITY IN DRINKING WATER

HEALTH EFFECTS BRANCH

CRITERIA AND STANDARDS DIVISION

OFFICE OF DRINKING WATER

US ENVIRONMENTAL PROTECTION AGENCY

Washington, D.C.

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INTRODUCTION/ABSTRACT

This general overview is designed to assist those involved with public health and drinking water (public health officers, officials, medical personnel, local, state and federal administrators) to better understand, interpret and implement EPA's regulations for radioactivity in drinking water. A public health official is often the one who receives a distressed call from a local water supply official who has just received the analysis of radioactivity in the local drinking water supply. Several questions come up such as:

What is a curie?

What do the numbers mean?

How bad is it?

What does that do to people?

Why haven't we noticed this before?

What evidence do you have that that really happens?

How many effects can we expect and how soon?

What must we do immediately?

What can we do to solve the problem?

How much will it cost?

How does this risk compare to others?

In this presentation the general nuclear properties are shown by using naturally occurring isotopes such as radium, radon and uranium as examples. The units of radioactivity (curie, rad, rem) are explained and demonstrated in describing natural radiation in our surroundings and bodies as well as man-made radiation from medical x-rays, TV, fallout, industrial uses and nuclear power plants and other sources. The

health effects discussed include birth defects, genetic damage, cancers, leukemias and others. Several specific examples are given in each disease area as well as their relative importance or rate of occurrence. The risk (in deaths/million people exposed/yr) is tabulated for radioactivity and compared to several other causes including disease, accidents and weather. Possible methods for reducing the radioactivity in drinking water are described and include: alternate well construction and treatment such as softening and reverse osmosis. Flow charts are provided that show how to interpret measurements of radioactivity in drinking water and what additional measurements may be required.

I PHYSICAL CHARACTERISTICS OF RADIOACTIVITY

A GENERAL NUCLEAR PROPERTIES

An atom consists of a heavy concentration of mass at the center (the nucleus) surrounded by shells of electrons in different orbits (see Figure 1). The primary constituents of the nucleus are neutrons and protons. The neutrons have no charge while the protons have a positive charge. The orbital electrons have a negative charge and are equal in number to the protons, making the atom neutral in overall charge. Of the several orbits an electron can occupy, each orbit has a maximum number of electrons that it can hold. How atoms interact with each other (i.e. their chemistry) depends upon how many electrons are in the outermost orbit. Due to the energy requirements of the atom, electrons tend to fall into lower orbitals first until the maximum number for that orbit is achieved. Higher orbits are then filled in succession. By the input of energy, electrons can be moved to outer orbits. They will spontaneously "fall" to lower orbits, much like water flows downhill, until the maximum number for that orbit is reached. The energy lost in this process is emitted as light or x-rays.

For example, the characteristics of the noble gases can be understood using the idea of electron orbits. They all correspond to filled outer electron orbits. If the first orbit is filled the atom is helium (He). When the orbits

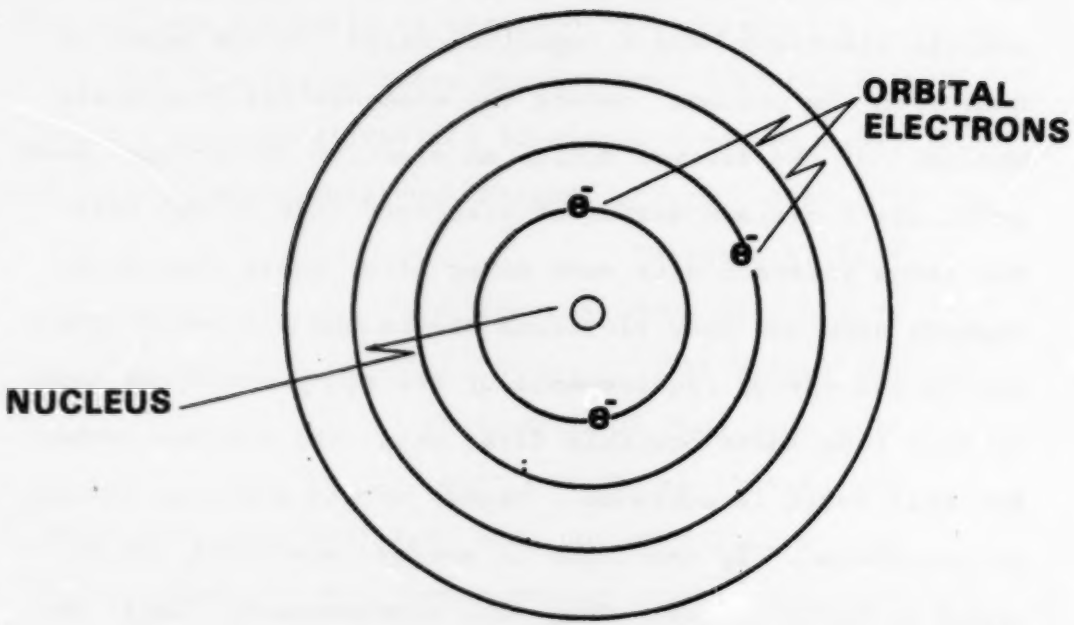

Figure 1 Schematic drawing of an atom. The example given here is one of the simpler elements called lithium.

are each completely filled the atom has greater stability or is less reactive -- hence the inert gases. (The names of the elements and their chemical symbols are shown in Appendix I). If the first and second orbitals are filled, the element is neon. This sequence continues through Argon (Ar), Krypton (Kr), Xenon (Xe), and Radon (Rn). Radon is a gas and is both inert and radioactive. There are different kinds (isotopes) of radon determined by the number of neutrons in the nucleus.

The chemical properties of an atom are determined by the electrons, because these are the parts of the atom that can come close enough to interact with other atoms under normal circumstances. The atom in Figure 1, because it has three protons and three electrons, is a lithium atom. It is lithium regardless of the number neutrons in the nucleus or electrons in the orbits.

Atoms are grouped into chemical families. The lithium atom in Figure 1 has two electrons in one orbit and a third in the outer orbit. Other atoms with a single outer electron; sodium, potassium, rubidium and cesium, will have chemical properties similar to (but not identical with) those of lithium. Radium, which has two outer electrons, behaves like calcium, which also has two outer electrons. For example, radium, like calcium, becomes incorporated into material such as bone.

The number of protons in the nucleus determines the element and its atomic number, as shown in Appendix I. A given element can have more than one particular number of neutrons. Variation in the number of neutrons does not change the chemical properties (the element is the same) but it produces considerable change in the stability of the element to radioactive decay. Atoms with the same number of protons but different number of neutrons are called isotopes. For example, if an atom has 86 protons, it is radon. There are three well known isotopes of radon containing 133, 134, and 136 neutrons. The atomic mass number is the total number of protons and neutrons in the nucleus and this sum is usually used to label isotopes. The three isotopes of radon have atomic masses of 86 + 133 = 219, 86 + 134 = 220 and 86 + 136 = 222. Symbolically these can be written as:

$$^{219}_{86}Rn \qquad ^{220}_{86}Rn \qquad ^{222}_{86}Rn$$

Since the atomic number of protons and the chemical symbol are synonomous, the number of protons is usually omitted in the nomenclature. The common isotopes of radon are usually written as:

$$^{219}Rn \qquad ^{220}Rn \qquad ^{222}Rn$$

Note that it is also acceptable to write them as:

Rn^{219} Rn^{220} Rn^{222}

or:

Rn-219 Rn-220 Rn-222

the latter form being used where superscripts are awkward.

The atomic mass numbers are not the exact masses of the atom. They only reflect the total number of neutrons and protons. They are, however, rough approximations of the actual masses. The energy released in radioactive decay comes from the differences in the actual masses through Einstein's well known equation -- $E = mc^2$. In this equation E is the energy, m the mass and c is a constant; viz, the speed of light.

It is a general rule of nature that a system will try to attain the lowest energy state or the most stable situation possible; e.g. water runs downhill, unlike charges attract each other causing an electron to "fall" into the orbit closest to the nucleus; snow falls to the ground. In this same sense, if a nucleus can move to a lower energy state by emitting radiation -- it will. Such a nucleus is radioactive compared to other nuclei which may be stable, and unable to lose energy by emitting radiation.

In general one might expect the nucleus to be able to emit all different kinds and combinations of radiations. However, because of this trend to stability and the nature of the nuclear force, the most likely (or most stable) radiations to be ejected are:

Emitted Particles	Process	Radiation Type
helium nucleus (two protons plus two neutrons)	alpha decay	alpha particle
electron	beta decay	beta particle
a kind of high energy x-ray	gamma decay	gamma ray

An alpha particle, the heaviest nuclear radiation, consists of two protons and two neutrons (A proton or neutron is about 2,000 times as massive as an electron). A beta particle is an electron emitted from the nucleus as a result of neutron decay. An electron can be "created" and ejected from a nucleus by a neutron decaying into a proton (which remains in the nucleus) and an electron (which is ejected as a beta particle). As a result of this process the nucleus has one more proton and thus has become the atom of a different element with atomic number one greater than the parent atom. A gamma ray is a form of electromagnetic radiation. Other forms of electromagnetic radiation are light, radio waves, infrared radiation, ultraviolet radiation and x-rays.

The process of alpha and beta radioactive decay leads to a different element while gamma decay does not. The isotope that decays is called the parent. The resulting

isotope (if a different element) is called the daughter. For example, ^{222}Rn decays by emitting an alpha particle to the daughter ^{218}Po (see Appendix II). This reaction is written:

$$^{222}_{86}Rn \longrightarrow {}^{218}_{84}Po + {}^{4}_{2}He$$

where the atomic numbers and atomic mass numbers have been included and the alpha particle is written in with its atomic numbers. Note that the atomic numbers and atomic mass numbers balance on the two sides of this equation. Note that the atomic mass decreased by 4 due to the loss of two neutrons and two protons, and the atomic number decreased by 2 due to the loss of two protons. Beta decay causes the atomic number to increase by one. Beta decay can be described as a neutron in the nucleus converted to a proton. An example of beta decay is ^{228}Ra which decays to ^{228}Ac. This reaction is written:

$$^{228}_{88}Ra \longrightarrow {}^{228}_{89}Ac + \beta^{-}$$

where the greek symbol is used for the beta particle and the minus sign shows that it is an electron. The atomic numbers

and atomic mass numbers balance in this equation since the atomic number for an electron is -1 and its atomic mass number is zero. Gamma decay changes neither the atomic number nor the element; it only involves a loss of energy.

Alpha, beta and gamma radiations have many different energies and masses and thus produce different effects as they interact with matter. Each of these radiations are capable of knocking an electron from its orbit around the nucleus and away from the atom. This process is called ionization. If an electron is moved to an orbit further from the nucleus the atom is said to be excited. The atom will then decay by the electron returning to the inner orbit and emitting radiation. We see this kind of radiation from a light bulb.

It is by ionization that radiation is detected. Moreover the process can be beneficial to humans through therapeutic and diagnostic medicine. The ion being highly reactive permits easy detection. The highly reactive ion can also lead to deleterious effects in humans such as cancers and leukemias. Alpha, beta and gamma radiations can be ionizing and are the subject of this discussion. (Among non-ionizing radiations are electromagnetic radiations such as light, microwaves and radio waves.)

Not all atoms are equally stable and different isotopes characteristically decay at different rates. The concept of

half life is used to quantitatively describe these differences. The half life of an isotope is the time required for one half of the atoms present to decay. Half lives can range from billions of years or more (the half life of ^{238}U is 4.5×10^{9}yr) to millionths of seconds (the half life of ^{214}Po is 164×10^{-6} sec) and even less.

Another way to describe the differences between the nuclear radiations is their ability to penetrate matter. A comparison is shown in Figure 2. In general most alpha particles can be stopped by a piece of paper while most gamma rays can pass through the human body (as do x-rays). The fact that the alpha particle can be stopped in such short distances, shows that it deposits more energy in a small distance; this does more damage per unit volume than the other radiations.

Many isotopes exist naturally such as the ^{40}K in our bodies, the ^{14}C produced by cosmic rays used to date old manuscripts and the naturally radioactive series (see Appendix II). There are three naturally occuring radioactive series: the uranium, thorium and actinium series. These series involve a sequence of alpha and beta and gamma decays involving heavy nuclei. They start respectively with ^{238}U, ^{232}Th and ^{235}U and all end with a different stable isotope of lead (Pb). In the middle of each series a different isotope of the gas radon (Rn) is formed. The implication of a gas being formed is important to human health

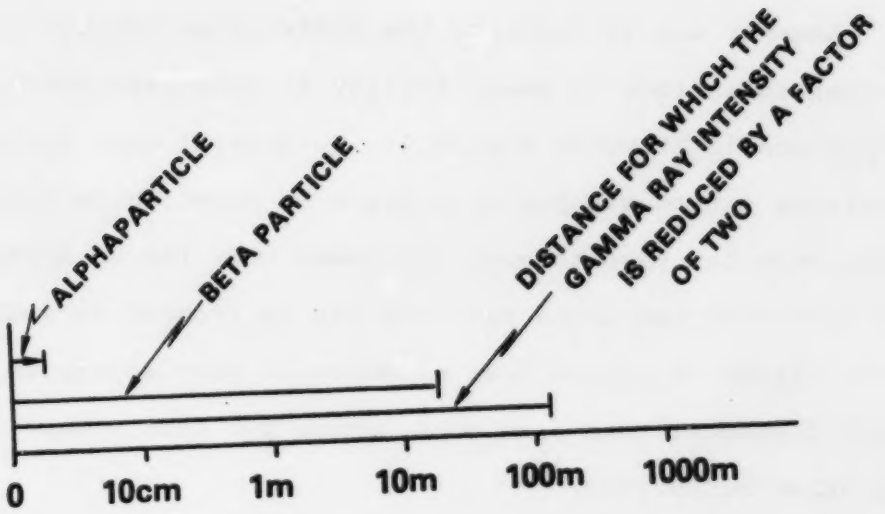

Figure 2 Range of nuclear particles in air with the same energy (3 MEV). Note that the scale is logarithmic.

since gasses have more freedom to move. For example, if ^{226}Ra is present in drinking water, and decays to ^{222}Rn, it may enter a home within the drinking water, and enter the body by inhalation.

Since each member of a radioactive series decays at a different rate they may not all be present in the same amounts. The series might be thought of as a series of different sized funnels in sequence, with the smaller spouts representing the longer lifetimes. There is a possibility that the isotopes may decay from rocks into adjacent ground water aquifers. In this process the parent isotopes could remain in the rock, while the daughters move into the water by recoil due to decay of the alpha particle. The parent and daughter nuclei are different elements and thus will likely move and react chemically at different rates. The relative amounts of parent and daughter nuclei could be different from what they would be were they both in the rock. For this reason it is essential to know how much of each isotope is in the water. All members of a series that are important to human health need to be monitored.

Fission can also contribute radioactivity to drinking water. This process, the source of immense energy, is triggered by adding a neutron to certain nuclei. The phenomenon occurs for heavy nuclei, the classical examples being ^{235}U, ^{232}Th and ^{239}Pu. When a neutron is added, each

of these isotopes break into two roughly equal parts. Each of the parts (called fission fragments) is itself a radioactive nucleus and decays through a sequence of isotopes by beta and gamma decay. Whether a radioisotope is man-made or naturally occurring can be determined on the basis of alpha particle emissions. A naturally occurring decay series includes alpha emissions, while a man-made radioisotope involves a decay series lacking in alpha emissions (except for the heavy transuronic elements).

B UNITS OF RADIOACTIVITY

Generally units such as mg/l, micrograms/liter or ppm are used to describe the concentrations of pollutants, toxic and hazardous substances. However, certain unique properties of radioactive substances preclude the use of these units and require different units to directly compare the health effects of different radionuclides.

Three important units are needed to describe radioactivity:

- how many radiations are emitted per second (or decays/sec or disintegrations/sec)
- how much punch the tissue receives or energy imparted to matter (called dose)
- how much biological damage is done by the radiation

For radioactivity the number of particles emitted (alpha, beta or gamma) is what does the damage and not the mass of the

radionuclides. Thus it is essential to have a unit that describes the activity or number of particles emitted. The activity is related to the half life, and thus longer half lives mean lower activity. By definition one gram of radium is said to have 1 curie (1 Ci) of activity. By comparison, 1 gm of ^{238}U has an activity of 0.36 millionth of a curie (or 0.36 microcurie - see Table 1 and Appendix II).

The effect of radioactivity depends not only on the number of radiations emitted/sec but on the kind of radiations (alpha, beta or gamma) and their energies. These latter two properties are described in terms of the dose or punch given to tissue or matter.

A common unit of dose (or radiation absorbed) is called the rad, and one rad deposits one hundred ergs (a metric unit of energy) in one gram of matter (to get perspective on the size of an erg, 10 million ergs/sec is one watt). In general these units are quite large and engineering shorthand is used to describe the day-to-day activities. Table 1 gives the meaning of some useful and commonly used prefixes. Thus a millimeter is one thousandth (1/1000) of a meter and a kilogram is a thousand grams. Similarly 1 picocurie is a million millionth of a curie and is abbreviated 1 pCi. Also 1 millirad (1 mrad) is one thousandth of a rad. These latter are common levels of activity and radiation strength found relating to drinking water. (The Roentgen (R) is a similar unit used in describing x-ray and gamma ray exposure. The basic differences between the R and the rad centers around a unit of exposure vs. a unit of energy absorption.)

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Table 1 Engineering shorthand and greek prefixes.

GREEK PREFIX	ABBREVIATION	VALUE	ENGINEERING SHORTHAND	
mega	M	1,000,000	10^{6}	
kilo	k	1,000	10^{3}	
milli	m	$\frac{1}{1000}$	10^{-3}	ONE PART PER THOUSAND
micro	μ	$\frac{1}{1,000,000}$	10^{-6}	ONE PART PER MILLION(ppm
nano	n	$\frac{1}{1,000,000,000}$	10^{-9}	ONE PART PER BILLION(ppb)
pico	p	1/1,000,000,000,000	10^{-12}	
femto	f	1/1,000,000,000,000,000	10^{-15}	

Because of the particle mass and charge, 1 rad of alpha particles creates more damage than 1 rad of gamma rays. To compensate for this difference in effect a new unit is invented -- the rem, for radiation equivalent man. This is called the dose equivalent. The dose is measured in rads and the dose equivalent is measured in rem. Frequently, however, the rem is called the dose. The dose equivalent is a measure of harm and is not generally an exact measurement; it is a useful administrative unit. The rad and rem are related by a quality factor as follows:

number of rems = Q times the number of rads

where Q is the quality factor which has been assigned the following value:

Q = 1 for beta particles and all electromagnetic radiations (gamma ray and x-rays)

= 10 for neutrons from spontaneous fission and protons

= 20 for alpha particles and fission fragments

(The quality factor for alpha particles was taken to be 10 at the time regulations were promulgated for radioactivity in drinking water.)[9]

The average human in the U.S. receives from cosmic rays (high energy protons from outside the earth) and natural background radiation about 100 mrem/yr[1]. This can vary depending on where one lives and the kind of a structure in which one lives and works in. The higher the altitude, the

less protection we get from the earth's atmosphere. Thus people in Leadville, Colorado receive from cosmic rays 110 mrem/yr while people at sea level (like Washington, D.C.) receive about 20 mrem/yr. Flying coast-to-coast can add as much as 5 mrem per flight.

A selected population in the U.S. is subjected to diagnostic x-rays that will contribute about 80 mrem/yr on the average over the whole population. A smaller group will receive additional exposure to ionizing radiation from the diagnostic use of nuclear isotopes and a still smaller group is exposed to therapeutic ionizing radiation (as in cancer treatment). People who receive radioiodine treatment of thyroid condition can give their family members a dose as high as 2,000 mrem[2]. Color TV can lead to exposures as high as 1 mrem/yr. Fallout from nuclear weapons testing may contribute a few mrem/yr and effluents from nucler power plants may contribute a small fraction of a mrem/yr. Exposure from dental x-rays and occupational exposure to small groups contribute additional dose. From the sum of these exposures, the population in the U.S. is exposed to an approximate dose of 200 mrem/yr. Table 2 lists the sources of human exposure to radiation.

Although the background radiation level can vary considerably with altitude, few people live at high altitudes. Thus roughly two thirds of the population of the U.S. receives a dose of ionizing radiation in the range 180-220 mrem/yr[3]. The statistical geographical variation (two standard deviations for this case) is 8.5 mrem/yr[4].

Table 2 Sources of radiation for people in the United States.

SOURCE	
NATURAL RADIATION	
COSMIC RAYS	45
EXTERNAL SURROUNDINGS	40
INTERNAL(MAINLY ^{40}K FROM FOOD AND DRINKING WATER)	20
MAN-MADE RADIATION	
DIAGNOSTIC X-RAYS	80
RADIOPHARMACUTICALS	16
FALLOUT	3
NUCLEAR POWER PLANTS	0.1
COLOR TV	1
MINING AND MILLING U AND PHOSPHATE ROCK	5
OCCUPATIONAL EXPOSURE	0.8
CONSUMER PRODUCTS	0.3
TOTAL APPROXIMATELY	**200 mrem/yr**

II HEALTH EFFECTS OF RADIOACTIVITY

A GENERAL

Knowledge regarding the health effects of doses of ionizing radiation requires data concerning the relationship between dose and effect in humans. However, for moral reasons we cannot deliberately expose humans to radiation on an experimental basis. Thus we have to depend on information from experiments with animals or from epidemiological studies on human exposure to ionizing radiation. There are difficulties and problems with both of these approaches. In spite of these difficulties, much is known about the effects of ionizing radiation in humans.

The effect of any injury or insult to a human may not be the same as that to animals and vice versa. Rats and mice seem unaffected by tobacco smoke but humans can develop lung cancer from smoking. Perhaps the most toxic substance known for animals - 2,3,7,8 tetrachlorodibenzo-p-dioxin (popularly called dioxin) is much less toxic in humans[5]. Effects in animals do not in general scale up for humans[6]. Thus doubling the dose for an animal twice as large may not produce the same effect. The effect cannot be simply predicted by the proportionality of the weight. Thus, the biological differences between humans and animals impede accurate prediction of the effect on humans based on the effect in animals. In fact, assuming that what affects animals will also affect humans can be wrong. However, it is an EPA policy to use animal data in setting standards for humans.

Although the effects of ionizing radiation on humans is much better known than the effect of many other environmental pollutants, it cannot accurately and definitely be predicted from known animal effects. An example of this problem is the genetic effects of ionizing radiations on survivors of the atomic bomb explosions at Hiroshima and Nagasaki. The incidence of genetic effects in the descendants has been far less than is predicted based on animal studies.

There are problems in determining effects on humans based on epidemiological studies. Perhaps the largest difficulty is the inaccuracy or incompleteness of the cause of death on death certificates. For example, heart attack caused by the strain of another disease might appear on the death certificate as the cause of death rather than the infirmity producing the strain. In most cases the actual dose received is not well known. In general this kind of information suffers from lack of control. There are many variables and it may not be clear if the effect is really due to ionizing radiation or another cause.

Our bodies may be exposed to both external and internal radioactivity. For exposures to drinking water, the internal exposures are the most important. Once a radioisotope enters the body by ingestion or inhalation (in the case of a gas such as radon), it will move to locations determined by the body's metabolism and chemistry. In some locations such as bone, it remains for relatively long periods of time. In others, it may pass through in relatively short-periods of

time. The time duration for the body to eliminate one half the original concentration is called the biological half life, while depending on the isotope may vary from minutes to years. In any case, different parts of the body can receive differing doses of radiation. Note that the biological half-life is not the same as the radioactive half-life. Biological half-life is a property of the body and radioactive half-life is a property of the nucleus.

Dosimetric models have been developed to determine the dose delivered to each part of the body from an ingested or inhaled radioisotope. The two models of importance to drinking water are ingestion (the gastro-intestinal model)[7] and inhalation (the lung model)[8]. The lung model is important because each naturally occurring radioactive series includes a gas (radon) which can be released from water sources in the home and ultimately inhaled by the occupants. These models are described in more detail in the ICRP publication number 30[9].

The gastro-intestinal (G.I.) model separates the G.I. system into four parts; the stomach, small intestine, upper large intestine and lower large intestine. The model then follows the radioactivity into the blood and organs. A biological half life is associated with each of these compartments along with the radioactive half life. Other important variables considered are as follows: the chemical compound

of which the isotope is a part (e.g., carbonate, protein, sulfate etc.), the age of the person involved, and whether the daughter products are radioactive and/or toxic (e.g., the series end at lead which is stable radioactively but is toxic chemically). With this model, as with most others, the greatest contribution to uncertainty is the lack of knowledge of the body's metabolism. Other degrees of uncertainty derive from neglecting consideration of chemical toxicity and restricting the consideration of health effects to the nearest tissue and bone. Thus, in the gastro-intestinal (GI) tract, normally only the mucosal layer is considered, and for bone exposure, only the top 10 micrometer layer of bone surface is considered.

Current model estimates indicate that the ingestion of 10 pCi/day of radium (or 5 pCi/l if 2 l/day is consumed) produces a dose of 150 mrem/yr to the skeletal bone[10]. Using models the dose resulting from the maximum intake of several man-made isotopes is shown in Appendix III.

Two ways of categorizing exposure are whole body dose or dose to a critical organ. The former is important when the radiation is external; however, a radioisotope inside the body often migrates primarily to a certain organ, called the critical organ. Some examples of metabolic fates

of several isotopes are shown in Table 3. Some organs are far more sensitive to radiation than others. Therefore the exposure or dose allowed to the whole body (all organs) may be different than the dose allowed to the individual organs.

At levels above 100 rem total dose equivalent, deleterious effects in humans can usually be observed. For low doses, such as those of the order of background radiation level, there is no well demonstrated observable adverse effect. (See Table 4)[12]. One problem in determining the dose-response curve is that the probability of an effect at low levels is very small (on the order of one in a million). Therefore, in order for health effects studies to be statistically valid, the number of people exposed would have to be on the order of hundreds of millions, or more. Also, many of the deleterious effects can occur spontaneously, or from causes other than radioactivity, the numbers of people exposed that is required by the statistical analysis is prohibitively large. Thus, we may never be really sure what the effects of low level radiation are. An overview of the current understanding of the dose effect relationship is shown in Figure 3.

Table 3 Some examples of organs favored by particular elements

ELEMENT	CRITICAL ORGAN
Ra	BONE
I	THYROID
U	KIDNEY
Sr	BONE MARROW
Co	LOWER LARGE INTESTINE
Cl	STOMACH

Table 4 Effects for various doses of ionizing radiation. The effects for chronic exposure are annual estimates.

ABSORBED DOSE(rem)	EFFECT
ACUTE EFFECTS	
10,000	DEATH IN A FEW HOURS
1,200	DEATH IN SEVERAL DAYS
600	DEATH IN SEVERAL WEEKS
450	$LD_{50/30}$ (LETHAL DOSE TO 50% IN 30 DAYS)
100	POSSIBLE TEMPORARY IMPAIRMENT BUT PROBABLE RECOVERY
CHRONIC EFFECTS(predicted)	
5	60-1000 GENETICALLY DETERMINED ILLNESSES PER MILLION PEOPLE EXPOSED
1	100-200EXCESS CANCERS PER MILLION PEOPLE EXPOSED
1-10	LOWEST LEVEL FOR WHICH DELITERIOUS CHRONIC EFFECTS HAVE BEEN DEMONSTRATED
0.15	THIS DOSE EQUIVALENT TO THE BONE CAUSES 100 EXCESS CANCERS PER MILLION PEOPLE EXPOSED PER LIFETIME

The problem described in Figure 3 is to determine what the relationship is between the dose level and the effect for low doses. If the known curve is as shown for number 1 then it is possible that a linear extrapolation is correct (Curve b). A curvilinear (quadratic) extrapolation (Curve c) is also possible. However if there is a level below which no effect occurs (threshold) then Curve d might be correct. If the dose-effect curve is steep as shown in Curve 2 then the linear extrapolation (Curve b) might overestimate the effect whereas the extrapolation d might be more reasonable. Curve a suggests that the effect can be higher than the linear extrapolation.

The assumption that EPA feels is prudent and advisable is linear, no threshold (Curve B). It is felt that this is most likely a conservative approach and probably if anything overprotective. Thus knowing that there is insufficient information to determine the effect of low doses of ionizing radiations on humans, the possible effects are estimated using a linear extrapolation from data for high doses.

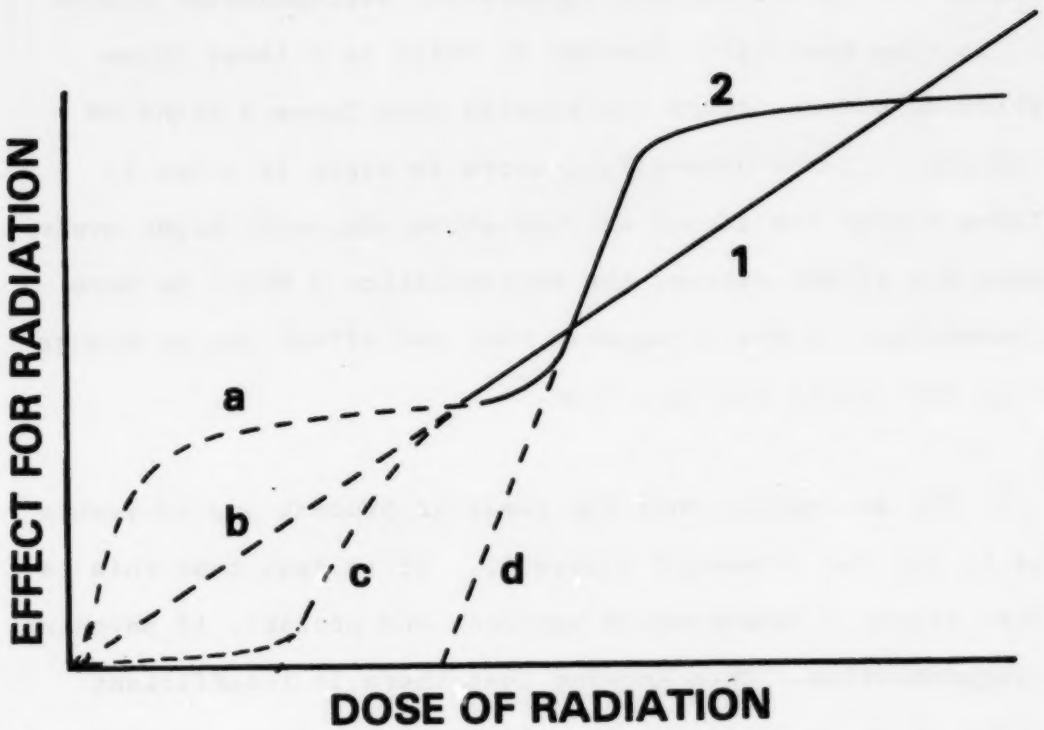

Figure 3 Different possible dose-effect curves for low level ionizing radiation.

The dashed lines are for the dose range where the effects are not known.

Although the effects at low doses are not known, the linear extrapolation from high doses can provide some numbers to work from. Figure 4 shows the number of deaths for annual exposure of a million people to radium in the drinking water. The assumption used to generate the curve is the linear, non-threshold one and it must be understood that it does not represent actual data. Using this curve one can get a rough idea of the possible effects of radium in drinking water if the linear non-threshold assumption is valid.

B HEALTH EFFECTS

There are three general areas where radioactivity produces deleterious effects on humans. (Reference 12 is a general reference for health effects). Some examples of the effects in these areas are:

Developmental and Teratogenic Effects

- Effects on the Fetus
- Developmental Abnormalities (skeleton and central nervous system)
- Embryo Lethality

Genetic Effects (effects in subsequent generations)

- Mutagenic Changes in DNA
- Hereditary Effects
- Diseases Caused by Mutations
  - Dominant/Recessive Diseases
  - Chromosomal Anomalies

Somatic Effects (effects in the person exposed)

- Carcinogenesis (including Leukemia)
- Cataract of the Lens of the Eye
- Non-malignant Damage to the Skin
- Gonadal Cell Damage/Impairment of Fertility
- Life Span Shortening

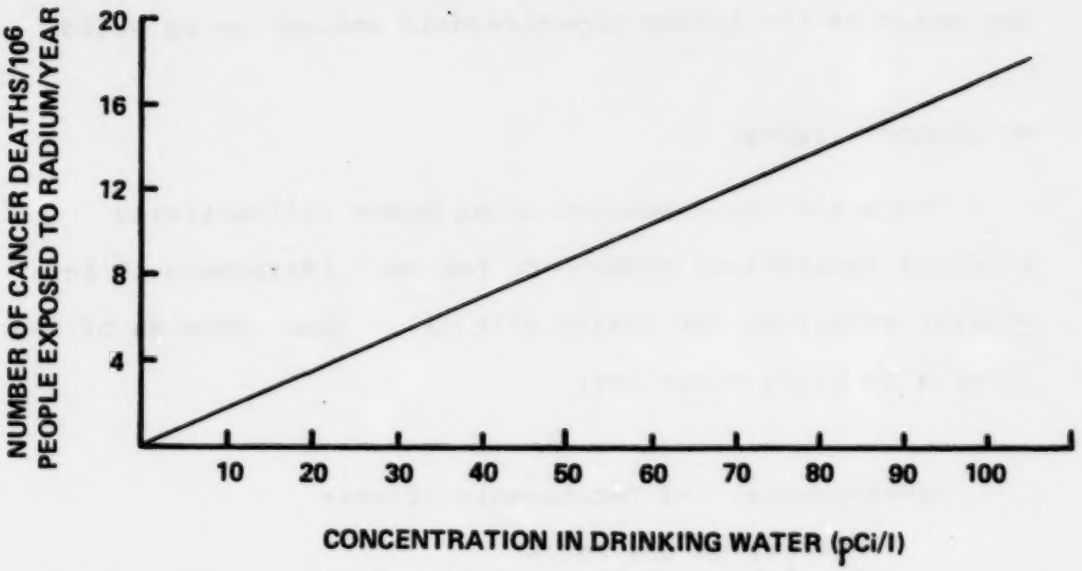

Figure 4 Plot of the number of deaths for annual exposure to radium in drinking water if the linear non-threshold assumption is valid.

The acute effects of ionizing radiation appear within 30 days as a variety of tissue changes or syndromes. Some effects are lethal and some are not.

Doses of 100,000 rad or more to animals usually cause inactivation of many substances needed for the basic metabolic processes of the cell and tissues and thus lead to an immediate death. Doses of about 10,000 rad produce hyperexcitability, incoordination, respiratory disease, possible damage to the nervous system and lead to death in a day or two. In the dose range from 900 to 10,000 rad, most animals die in 3 to 5 days due to morphologic changes or damage to the gastrointestinal (GI) tract. For doses in the range of 300 to 900 rad, death usually occurs in 10 to 15 days due to alterations in blood cells and blood forming organs (hematopoietic system).

Exposure of humans to doses at 50 rad or greater lead to radiation sickness. This is characterized by headache, dizziness, malaise, abnormal sensations of taste or smell, nausea, vomiting, diarrhea, decreased blood pressure, decrease in white blood cells and blood platelets, increased irritability and insomnia. Exposures of several thousand rads or more cause shock, abdominal cramps, cyanosis, coma and death. For doses in the range of 500 to 2000 rads, normal food and fluid intake is depressed, followed by dehydration, hemoconcentration, circulatory collapse and death. Nausea

vomiting, and some diarrhea can be the result of exposures of less than 500 rads. The body then seems to recover. But, a few weeks later there is an onset of chills, fatigue, petechial hemorrhages in the skin and ulceration of the mouth, pharnyx and intestine, impairment of immune mechanisms and hemorrhagic ulceration permitting entry of bacteria. Death, if it occurs, is usually between the third and sixth week.

Embryos have been shown to be especially susceptible to ionizing radiation. Those exposed in utero at Nagasaki and Hiroshima showed microcephaly (small brain) and mental retardation. Other exposed children suffered from congenital dislocation of hips, mongolism and congenital heart disease.

The nervous system of humans is usually found to be extremely radio-resistant in terms of morphologic changes but does demonstrate a variety of physiologic responses to relatively low doses of radiation. These effects include changed reception activity of the eye and changes in conditional reflex activity.

To understand genetic effects, let us examine how life begins. The creation of new life is determined by the union of sperm cell and egg cell forming a single fertilized egg. This is followed by millions of cell divisions. The blueprint for these cell divisions and for how the new life

grows and develops is found in the DNA molecule. The DNA molecule is a double helix string of atoms and carries the basic genetic information. As can be seen in Figure 5, the basic units of the DNA molecule are four bases labeled G, C, A and T. The chemical composition of the DNA molecule is seen more completely in Figure 6 where the polygons represent carbon rings (a carbon atom at each unmarked corner). Ionizing radiations can change the structure of the DNA molecule by changing the way the atoms are bonded or connected together (this occurs through the atomic electrons). For example two bases such as T could be in adjacent steps instead of alternate steps as shown in Figure 6. In that case ionizing radiation could break an electronic bond and the T bases would bond to each other instead of the structure as shown. Following that change the cell divisions would follow the new blueprint determined by the new DNA structure. This new pattern follows a new genetic blueprint and almost always leads to deleterious effects.

The effect of nuclear radiations important for human health effects is the ability to ionize atoms. The direct effect is thought to be ionization of the atoms of DNA in the cell and thus to change the cell's behavior. An indirect effect may occur when water in the cell is ionized. Human cells are about 75% water and when water is ionized it can produce the highly reactive HO ion (called the hydroxyl free radical). The HO can attack the DNA and do damage to it.

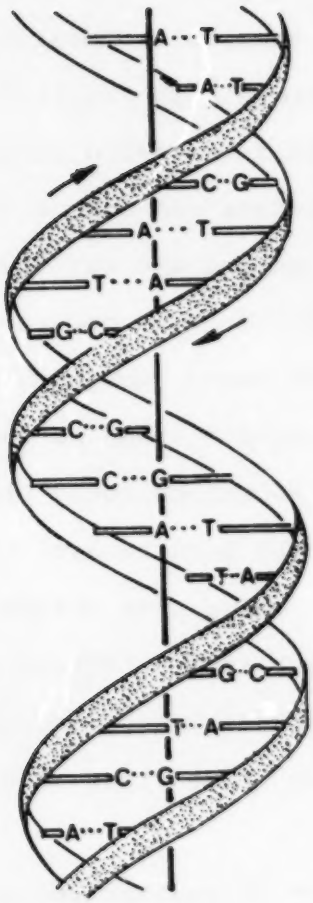

Figure 5 A schematic representation of the DNA double helix.

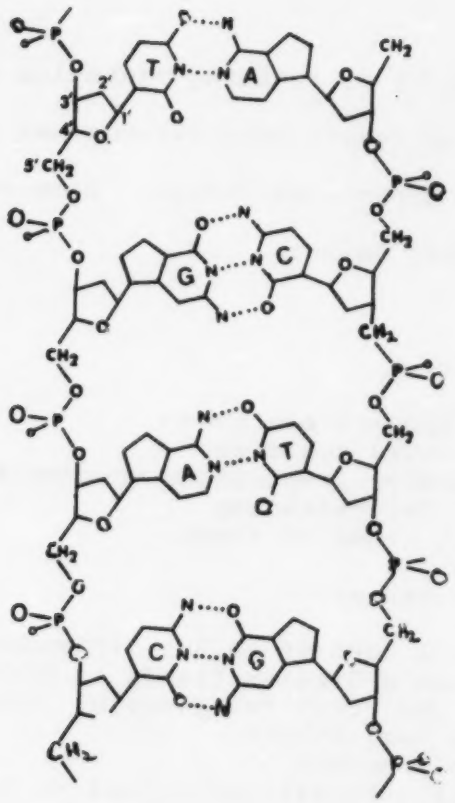

Figure 6 The DNA molecular structure. The base pairs are shown connecting the backbone like rungs of a ladder. The dots represent hydrogen like bonds.

Agents that can change the genetic code (called mutagens) can be found inside our bodies (the mechanisms are not well understood) or external to our bodies. External mutagenic agents include chemicals, drugs, elevated temperatures and ionizing radiation.

Genetic effects of ionizing radiation include abnormalities, recessive diseases (where both chromosomes in the pair have some defect) and chromosome damage. Some examples of these maladies are listed below:

Abnormalities

- extra fingers and toes
- short lived dwarfism
- progressive involuntary movements
- mental deterioration
- several kinds of anemia

Recessive Diseases

- PKU -- a form of mental deficiency
- Tay Sach's Disease (leads to blindness and death in the first few years of life)
- Sickle Cell Anemia
- Cystic Fibrosis
- Recessive Mutations Located in the X Chromosome (noted almost exclusively in males, since males only have one X chromosome)
  - Hemophilia
  - Color Blindness
  - A Severe Form of Muscular Dystrophy

Chromosome Damage

- Too many or too few can lead to embryonic death or miscarriage
- Broken Chromosomes can be involved in:
  - Diabetes
  - Schizophrenia

In general it is believed that mutations, whether spontaneous or induced, can be harmful even though the harm may be trivial and the effect may not show up for hundreds of generations. In general each new harmful mutant is eventually eliminated by reduced viability or gene extinction.

The number of mutations appears to be proportional to dose and since spontaneous mutations do occur, the concept of doubling dose is used; specifically, the doubling dose is that dose of ionizing radiation that will produce mutations equal in number to those spontaneously occurring. The doubling dose is in the range 20-200 rem for genetic effects of ionizing radiation. A cumulative dose of 5 rem per generation (or 170 mrem/yr for 30 years - the child bearing range) might in the U.S. produce 60 - 1,000 genetically determined illnesses of various sorts per million live births. About 4% of live born infants or 60,000 show evidence of hereditary defects. Thus, if this estimate is reliable, ionizing radiation can cause a 0.1% - 1.6% increase over the expected incidence of genetically determined illnesses. If the same exposure level is continued for several generations, the percentage of excess illnesses will increase due to the presence of the malady in the parents, increasing the probability of it occurring in the offspring. The effect level might eventually reach 300 - 7,500 cases per million live births or a 0.5% - 12.5% increase.

Of the somatic effects the most important are cancers. The mechanism causing cancer is not known at this time. Thus statistical data from animal and human epidemiological studies must be used. Again little is known about the actual effects of low dose. However by extrapolating from high doses the death rates can be predicted as shown in Table 5.

The estimates listed in Table 5 do not include several variables which will change the predicted effect level. The effect on the fetus or child is known to be higher (by perhaps a factor of 3 - 5). The effects shown have a different latency period varying from 5 - 25 years. For example, one would expect 1 case of leukemia/million exposed persons/yr/rem with the approximate distribution shown in Figure 7.

Other factors that can modify the predicted somatic effects of low level radiation are dose rate and biological variation. In general the effect of ionizing radiation on the human body is cumulative. This would imply that receiving 100 rem in a day would have the same effect as receiving 1 rem per day for 100 days. This is not true at high rates where receiving 50 rem/min for one minute is 3 times more destructive than receiving 1 rem/min for 50 minutes. Biological variation is due to the different sensitivity of body tissues and the existence of some repair mechanisms in the body.

Table 5 Expected death rates for somatic diseases.

DISEASE	NUMBER OF DEATHS/10^6 EXPOSED PEOPLE/YR/REM
CANCERS	
LUNG	0.4-1.5
BREAST	1.5-6.0
SKELETON	0.1-0.3
GI AND STOMACH	0.5-1.0
OVERALL	2.5
LEUKEMIA	2-4
LEUKEMIA (IN UTERO EXPOSURE)	25

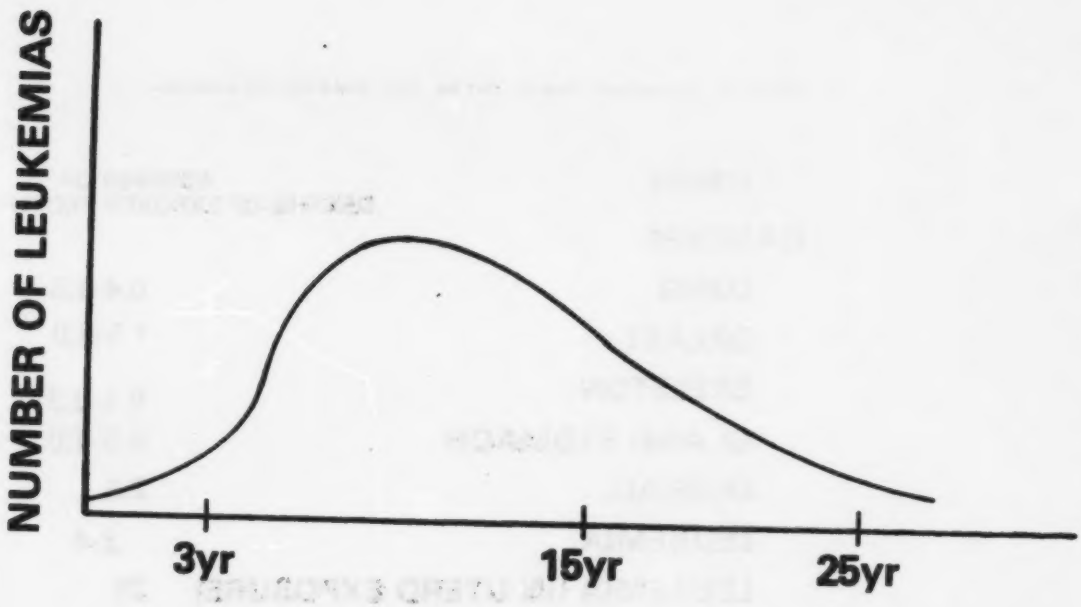

Figure 7 Distribution of leukemias in time after the dose

C RISK

In order to determine the importance of health effects the associated risk must be examined[13]. In assessing the overall risk that the source of the radioactivity presents to the body, the organs and the particular deleterious effect must all be considered. The overview shown in Figure 8 relates these factors.

One way to understand the importance of the risk from ionizing radiation is to compare it to other risks. The determination of a standard will depend in part on this comparison (also the resulting cost and social and political implications have to be considered). Table 6 shows the risks from several different causes and how they relate to the current EPA standards for drinking water (note that the EPA standard for Ra results in a dose to the bone surface of 150 mrem/yr, but the bone surface is less sensitive to radiation than other tissues so that it can tolerate an exposure rate thirty times greater than the whole body rate).

As can be seen from Table 6, the risk from radioactivity in drinking water (assuming that the MCL concentration was present) is of the same order as the risk from lightning, tornadoes and hurricanes. It is less than the risk from natural radiation from the earth's radioactivity and solar ultra violet radiation.

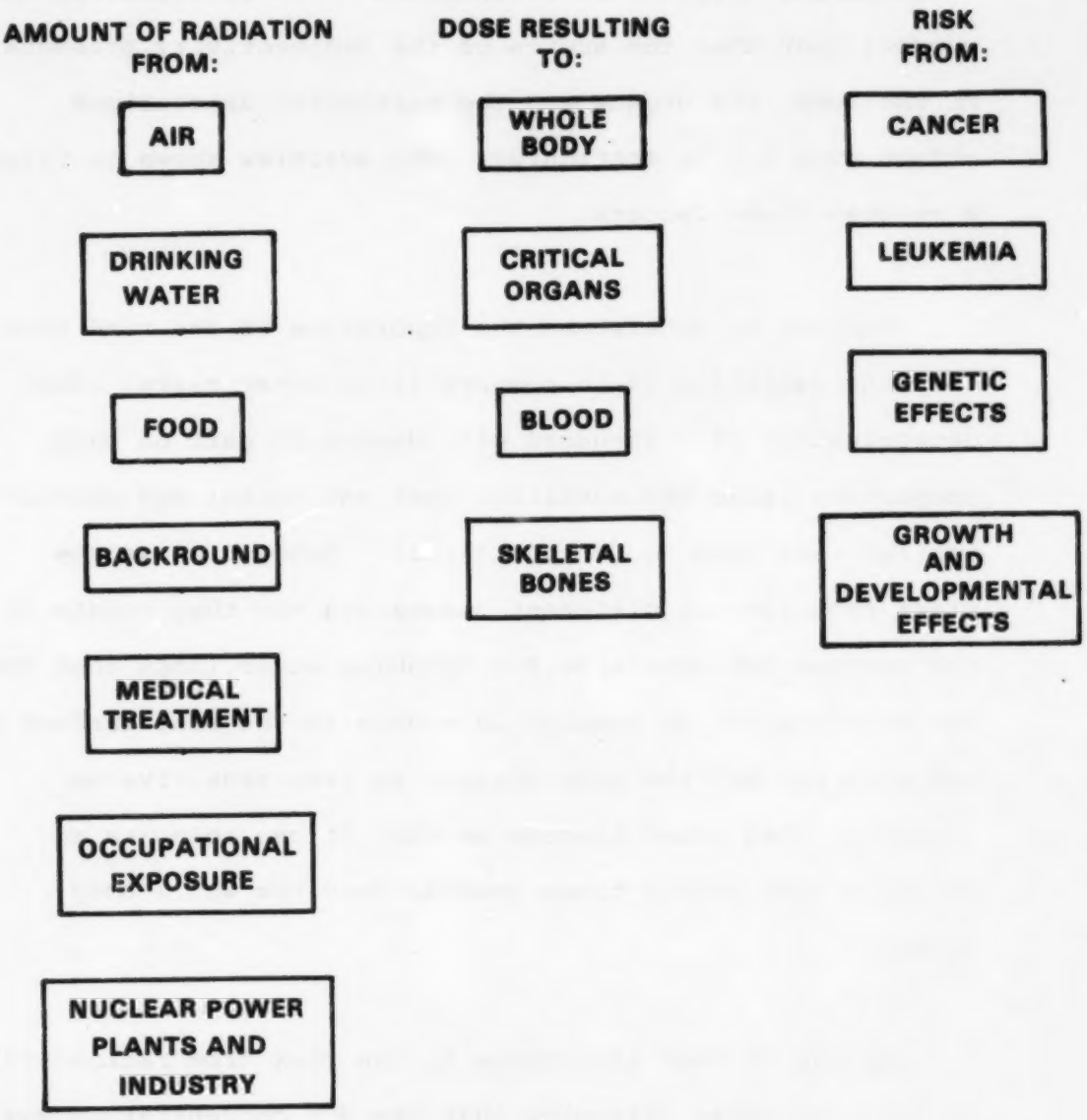

Figure 8 Overview of factors involved in determining risk from radioactivity in drinking water.

Table 6 Risks to people in the U.S. from various causes[14].

The units are deaths/million people exposed/year.

CAUSE	DEATHS/MILLION PEOPLE EXPOSED/YEAR (IN 1977)
ALL CARDIOVASCULAR DISEASE	4700
CANCER	1760
MAJOR CARDIOVASCULAR DISEASE	880
AUTOMOBILE	230
HOME ACCIDENTS	180
FALLS	85
AIR POLLUTION FROM FOSSIL FUEL POWER PLANTS	50
FIRE/BURNS	30
DROWNING	30
MELANOMA (SKIN CANCER THOUGHT TO BE DUE TO ULTRAVIOLET RADIATION FROM THE SUN) [15]	28
POISON	25
CANCER DEATHS FROM NATURAL RADIATION (100 mrem/yr)	20
CANCER DEATHS DUE TO MEDICAL X-RAYS	18
FIREARMS	9
AIR TRAVEL	7
ELECTROCUTION	6
CANCER DEATHS FROM DOSE TO BONE OF 150 mrem/yr (EPA STANDARD FOR DRINKING WATER)	1
ANIMAL & INSECT BITES	1
LIGHTNING	0.5
TORNADOS/HURRICANES	0.4

The total risk due to the ingestion of 10 pCi/day of ^{226}Ra (or 5 pCi/l when 2 l/day is ingested) lies in the range 0.7 - 3 cancers/ yr/million people exposed. ^{228}Ra is thought to have about the same toxicity as ^{226}Ra.

The only prudent approach to regulating radioactivity is to keep the levels to all exposure as low as possible considering health effects, feasibility and cost. Until more information is available, the dose-response curve will be assumed to be linear with no threshold. By adopting the attitude that all exposures cannot be eliminated, the regulator must recognize the risk and must also accept the role of establishing limits of exposure on the information available to him with the clear understanding that, as more information is obtained, more research completed, greater refinement of data accomplished, then regulatory levels may change. Once adopted, a regulation is subjected to repeated review and revision.

III POSSIBLE CONTROL TECHNIQUES FOR RADIOACTIVITY IN DRINKING WATER

If a water supply is not in compliance with the EPA regulations for radioactivity in drinking water (see the next section), then a number of different approaches can be taken to deal with the problem. A more detailed discussion of control techniques can be found in reference 16. A new well may be drilled, and used by itself, or its water may be blended with the more radioactive water to reduce the concentration. Bottled water may be used to replace water with high radioactivity. The primary technological methods available for reducing the concentration of radioactivity and ion exchange, lime softening and reverse osmosis.

There are two basic types of water softeners which remove some inorganics. The ion exchange method is the most common in a home. A zeolite resin is used to exchange sodium for heavy metals (which include radium). These units are regenerated with common table salt. Another method (lime softening) is done on a large scale at water purification plants, and involves adding calcium oxide or calcium hydroxide to increase the pH to the level where the metals will precipitate out. To understand how this technique works it is useful to remember that radium is chemically similar to calcium.

Another technique for removing impurities in water for small systems is reverse osmosis. Basically pressure is used to force water through a semi-permeable membrane. The water passes through the membrane but the impurities do not. A pressure of 50 lb/in^2 (a normal water pressure) can achieve 90% removal of impurities. Higher pressures can achieve higher efficiencies. Among other methods for removing radioactivity for large systems are distillation and electrodialysis. The latter is similar to reverse osmosis only an electric force is used to drive the water through a membrane.

IV RADIATION REGULATIONS

A GENERAL

The Federal Radiation Council (FRC) in its report to the President (1961)[17] recommended that the upper limit for exposure to workers in the nuclear industry be 5 rem/yr. The upper limit for exposure to the general public was set at 1/10 of this level while also allowing for an uncertainty of a factor of three making the overall fraction 1/30. Thus the upper limit for the whole body allowed dose to the general public is:

$$(1/30)\ 5\ \text{rem/yr} = 170\ \text{mrem/yr}$$

The limits set by EPA for drinking water are 5 pCi/l of Ra, 15 pCi/l of gross alpha particle activity (excluding U and Rn) and a total dose equivalent of 4 mrem/yr for man-made radioactivity[18]. As discussed earlier, 5 pCi/l of Ra produces a bone dose of 150 mrem/yr. The dose for other alpha particle emitters (except U and Rn) is variable and is estimated to be no more than 1/5 of the value for Ra.

The EPA levels (maximum contaminant levels or MCL's) were set on the basis of the above mentioned health effects and the removal cost of the radioisotopes. This is in keeping with the principle that radioactivity should be kept as low as reasonably achievable (ALARA), taking costs into consideration.

The existing regulations covering radioactivity were promulgated July 9, 1976 in the Federal Register (Vol. 41, No. 133, pages 28404-28409). The present discussion is meant to provide a simplified description of the radiation regulations, and should not be taken for legal purposes as a replacement.

Uranium and radon are both excluded from the current regulations but will be included in the future. Uranium was excluded because of the additional complexity of being both chemically and radiologically toxic. Radon was excluded because of its special characteristics as a gas.

Radioactivity in public water systems may be broadly categorized as naturally occurring or from man-made sources (such as nuclear power plants, fallout from nuclear weapons testing and from the use of radioisotopes in scientific laboratories, industry and medicine). Because of its toxicity and occurrence ^{226}Ra is the most important naturally occurring radionuclide. Although ^{226}Ra may occasionally be found in surface waters due to man's activity, it is usually found in ground water where it is the result of geological

conditions. In contrast man-made radioactivity is found primarily in surface water.

B NATURAL RADIOACTIVITY

The determination of concentrations of natural radioactivity begins with the measurement of the gross alpha particle activity. The gross alpha particle activity measurement is used as a screening technique. If the gross alpha particle activity is less than 5 pCi/l, the source is in compliance. If the gross alpha particle activity is greater than 15 pCi/l the maximum contaminant level (MCL) may be exceeded. Then a decision scheme is followed as shown in Figure 9. The MCL is exclusive of radon and uranium so their activity should be determined, in addition, if the gross alpha particle activity were greater than 15 pCi/l. Uranium and radon were excluded because of uncertainties about their occurrence, toxicity and route of exposure. In the future MCL's for uranium and radon may well be developed. If the gross alpha particle activity excluding radon and uranium is less than 15 pCi/l, the source is in compliance for gross alpha particle activity.

If the gross alpha particle activity is greater than 5 pCi/l, the activity of ^{226}Ra must be determined. If the ^{226}Ra concentration is greater than 3 pCi/l, then in addition, the ^{228}Ra activity must be determined. The total of ^{226}Ra and

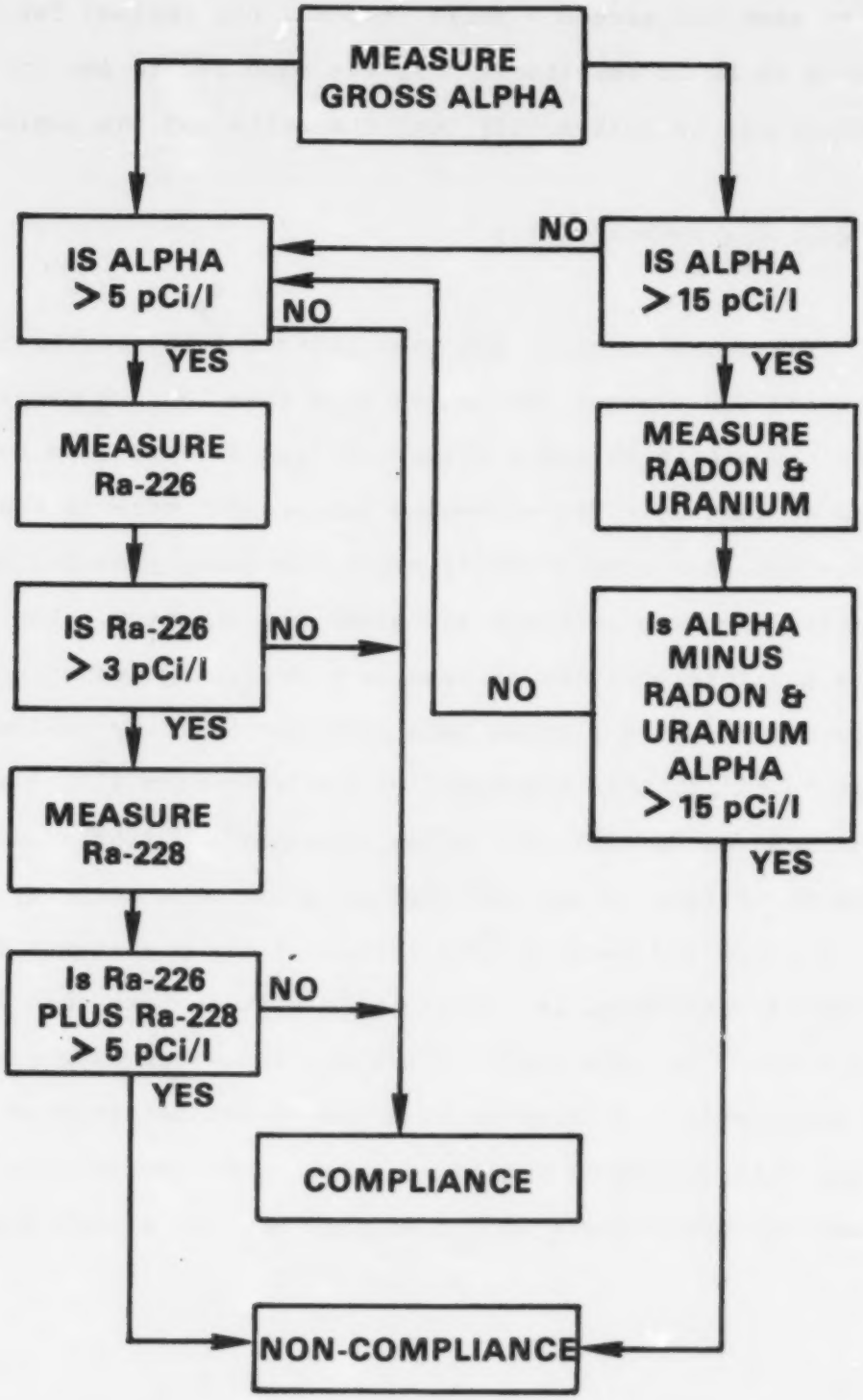

Figure 9 Flow chart for gross alpha particle activity monitoring (U.S. EPA, Las Vegas, Environmental Monitoring and Support Laboratory). Note that it is not a requirement that radon and uranium be measured if the gross alpha activity is greater than 15 pCi/l.

^{228}Ra must not exceed 5 pCi/l (the MCL for radium) for the source to be in compliance. If the supplier is not in compliance, he must notify both the State and the public.

C MAN-MADE RADIOACTIVITY

The measurement of man-made radioactivity levels is required for systems that serve more than 100,000 people. This radioactivity comes primarily from fallout from nuclear weapons testing. The screening measurement here is the gross beta particle activity since the decay products of fission are beta particle and gamma ray emitters. The gross beta particle activity is used as a screening technique (See Figure 10). If the gross beta particle activity is less than 50 pCi/l, then tritium (^{3}H) and strontium (^{90}Sr) activities must be determined. These isotopes are singled out because tritium is not included in gross beta activity since it is a gas and because ^{90}Sr is one of the most toxic fission products. As shown in Figure 11 ^{3}H must be less than 20,000 pCi/l and ^{90}Sr less than 8 pCi/l for the water supply to be in compliance. Tritium being a gas is not detected in the gross beta screening procedure. Also, the combination of these two must result in a dose that may not exceed 4 mrem/yr.

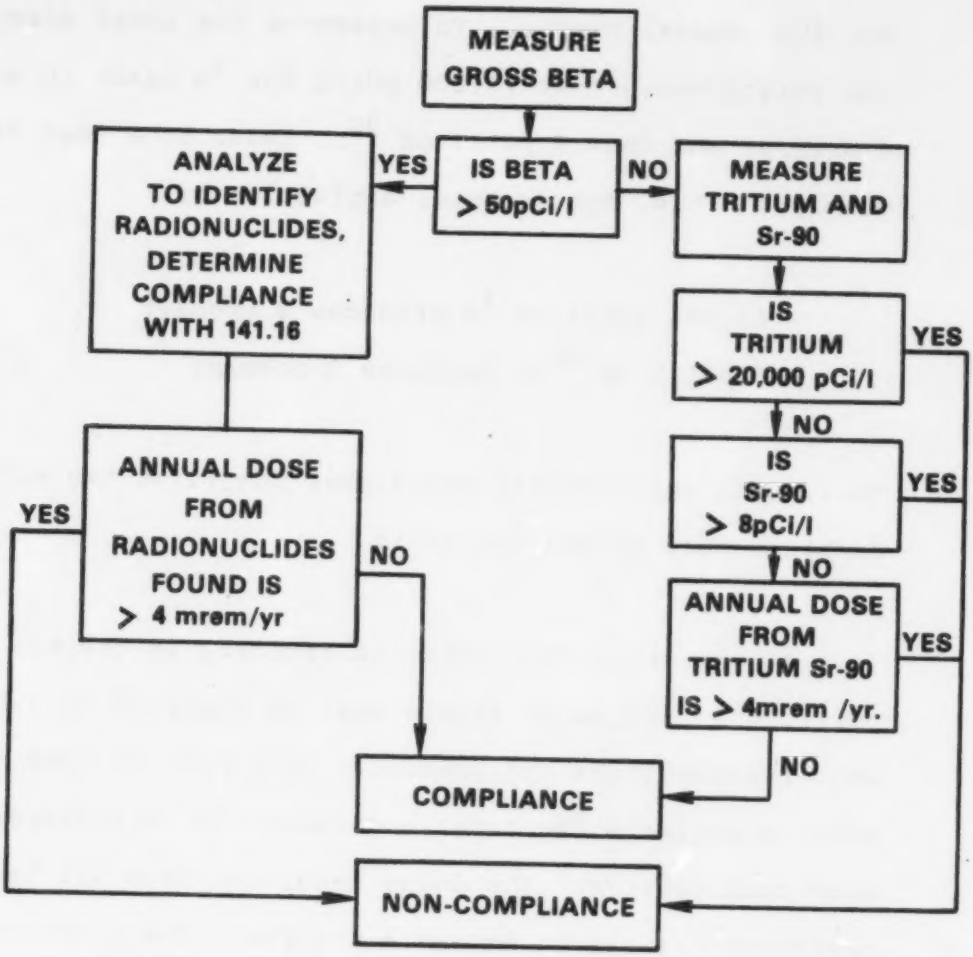

Figure 10 Flow chart for gross beta particle activity monitoring for a water source not designated as being contaminated by effluents from nuclear facilities serving more than 100,000 persons as designated by the State. (U.S. EPA Las Vegas, Environmental Monitoring and Support Laboratory)

The dose level of 4 mrem/yr was chosen because it was felt that the contributing concentrations were achievable. This dose level is well below the 170 mrem/yr recommended by the FRC for the general public. To determine the total dose, use the relationship that 20,000 pCi/l for ^{3}H leads to a dose of 4 mrem/yr and that 8 pCi/l of ^{90}Sr leads to a dose of 4 mrem/yr. Thus, for example, activities of:

- 15,000 pCi/l of ^{3}H produces 3 mrem/yr
- 6 pCi/l of ^{90}Sr produces 3 mrem/yr

Thus, each individually would pass the first two tests but combined they exceed the limit.

If the gross beta particle activity is greater than 50 pCi/l, then the water sample must be analyzed to determine what radionuclides are present. This must be done to be able to estimate the total dose since it is different for each radionuclide. The doses resulting from all these radionuclides cannot exceed 4 mrem/yr. The concentrations of the more important isotopes that result in a dose of 4 mrem/yr are listed in Appendix III.

As an example calculation, suppose that the results of analysis were ^{90}Sr-2 pCi/l, ^{137}Cs-50 pCi/l, ^{131}Ba-60 pCi/l, and ^{131}I-1 pCi/l. Then, the resulting doses can be calculated using Appendix III (as shown in Table 7). From Table 7, it can be seen that the source would be just in compliance since the total dose is less than 4 mrem/yr.

Table 7 Example calculation of total dose for man-made radionuclides.

ISOTOPE	CONCENTRATION (pCi/l)	CONCENTRATION IN pCi/l YEILDING A DOSE OF 4 mrem/yr (FROM APPENDIX III)	RESULTING INDIVIDUAL DOSE (mrem/yr)
^{90}Sr	2	8	1.0
^{137}Cs	50	200	1.0
^{131}Ba	60	600	0.4
^{131}I	1	3	1.3
		TOTAL	3.7mrem/yr

If a supplier is not in compliance with any part of the regulations, he must notify both the State and the public. The State is to be notified of monitoring results 10 days following the end of the month in which the measurement was made unless the source is not in compliance in which case notification must be made to the State within 48 hours. Initially all public water supplies must sample quarterly although only the composite need be analyzed. The results must be analyzed by June 24, 1980 for naturally occurring radioisotopes and by June 24, 1979 for man-made radioisotopes. After the initial sampling, each water supplier must monitor every four years unless the State requires it to be done more frequently. Any major change in the water supply or the addition of a new water source necessitates recompletion of the initial sampling process.

In place of the above requirements, the State must require further monitoring, if the water system is near a nuclear facility. Figure 11 shows the procedure for this analysis. The gross beta particle activity and ^{131}I activity must be measured quarterly. The gross beta particle activity can be determined for three monthly samples or their composite. For ^{131}I, the composite of 5 consecutive daily samples shall be analyzed once each quarter. Annual monitoring for ^{90}Sr and ^{3}H is to be conducted using quarterly samples or their composite.

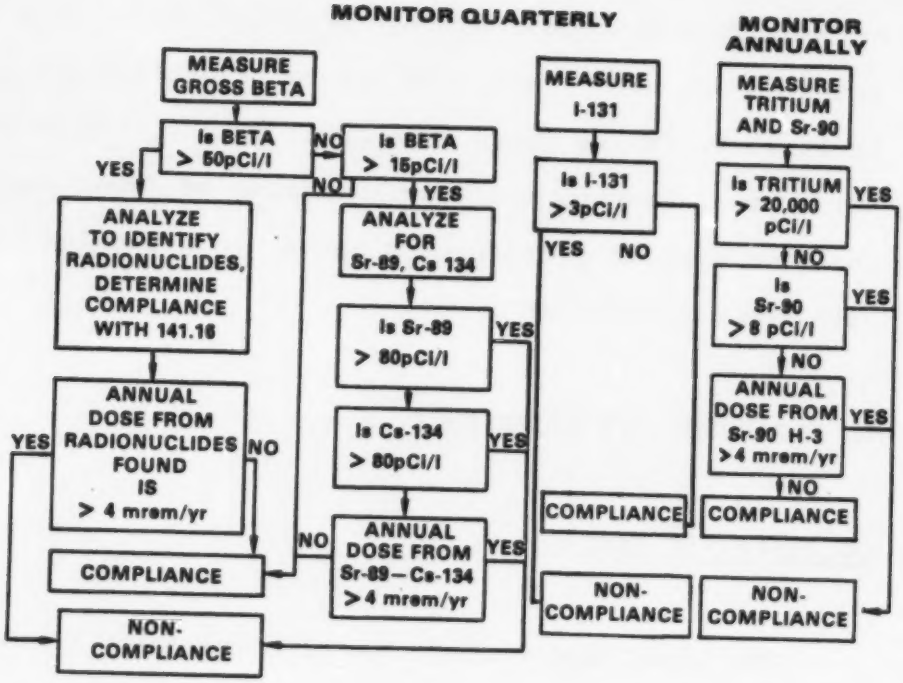

Figure 11 Flow chart for monitoring drinking water samples near a nuclear facility (U.S. EPA, Las Vegas, Environmental Monitoring and Support Laboratory)

If the gross beta particle activity exceeds 15 pCi/l for a nuclear facility, then ^{89}Sr and ^{134}Cs activities are sampled to assure that the sum of their resulting doses does not exceed 4 mrem/yr. These isotopes indicate recent contamination, such as from a nuclear facility, since they have short enough half-lives, and are not significantly present in fallout. Where gross beta particle activity exceeds 50 pCi/l, contributing radionuclides must be determined using the same summing procedure as above, to determine compliance with the 4 mrem/yr MCL.

D VARIANCES AND EXEMPTIONS

Guidance for Radium

The upper limit of the Federal Radiation Council (FRC) Range II guide for transient rates of radium-226 ingestion from both food and water is 20 pCi per day. Above this range, evaluation and application of additional control measures is always necessary (26 FR 9057, 1961). Provided that a comparable intake of radium via the food pathway is unlikely, exemptions for water supplies containing less than 10 pCi/l would be compatible with FRC guides. Occasionally, exemptions for concentrations exceeding 10 pCi/l, for limited times, may be acceptable.

In granting exemptions and establishing schedules for compliance, the primary agency should consider the extent to which the MCL for radium-226 and radium-228 is exceeded, the number of persons at risk, the daily intake of radium from sources other than drinking water and the duration of time before compliance is likely to be achieved. Since treatment methods are readily available, compliance schedules should provide for early installation of treatment processes or for the use of alternative water supplies.

Guidance for Gross Alpha

Since treatment technology exists to readily remove substantial quantities of radium from water, only exemptions for radium contaminants need be granted. No provision is made for variances. Exemptions for supplies having water concentrations of gross alpha activity up to 30 pCi/l are justified on the same basis as that provided for Ra-226 and Ra-228. If a thorough analysis of the water is performed to identify the alpha-emitting radionuclides, exemptions may be appropriate for limited time periods if the dose to bone from all alpha particle emitters, including Ra-226, is less than 300 mrem per year even though the gross alpha activity exceeds 30 pCi/l.

Guidance for Man Made Beta and Photon Emitters

Neither variance or exemptions should be necessary except in cases of malpractice. In cases where a water supply has been contaminated via chronic or intermittent releases, a variance or exemption may be necessary for a limited period of time to insure an uninterrupted supply of water for drinking and other purposes.

Current federal guidance for transient rate of intake provides limitations on food and water intake that are comparable to an annual dose equivalent of 50 mrem/year and contain a recommendation that for transient situations the dose should be averaged over one year (26 FR 9057). The variance and exemption limitation shall not exceed 50 mrem/year to any organ from radioactivity in finished drinking water (12 times EPA's 4 mrem/year standard). The maximum dose commitment for any one day from radioactivity in drinking water shall not exceed 10 mrem.

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GLOSSARY

Alpha Particle - a helium nucleus, two protons and two neutrons, $^{4}_{2}He$.

Atomic Mass Number - the total number of protons and neutrons in the atomic nucleus.

Atomic Number - the number of protons in the nucleus, identifies the element.

Beta Particle - an electron ejected from the atomic nucleus.

Curie - activity of one gram of radium or 3.7×10^{10} disintegrations/second.

Fission - process where a heavy nucleus splits into two roughly equal fragments, a few neutrons and releases a large amount of energy.

Gamma Ray - form of electromagnetic radiation emitted in nuclear decay.

Genetic Effect - a health effect that shows up in subsequent generations.

Half-Life:

Radioactive - time for one-half of the isotope to decay.

Biological - time for one-half of the atoms to move from that organ.

Ionizing Radiation - radiation that is capable of ionizing or removing one or more electrons from an atom.

Isotope - varieties of the same element with different masses (different neutron numbers).

Mutagen - substance that can change the structure of DNA and thus change the basic blueprint for cell replication.

Natural Radioactive Series - sequence of elements that exist naturally and decay into each other in a serial fashion.

Quality Factor - a factor that roughly approximates the relative differential damage that ionizing radiation can do to tissue.

Radioactive Decay - a process where the nucleus transforms to a lower energy state by emitting alpha, beta or gamma radiations.

Rad - amount of ionizing radiation that deposits 100 ergs of energy in one gram of tissue.

Rem - the number of rads times the quality factor -- a quantity that is more descriptive of the actual damage to tissue from ionizing radiation -- Radiation Equivalent Man.

Somatic Effect - health effect to the body exposed -- for ionizing radiation, mainly cancers and leukemias.

Teratogenic Effect - health effect to the fetus.

APPENDICES

I CHEMICAL ELEMENT SYMBOLS AND ATOMIC NUMBERS

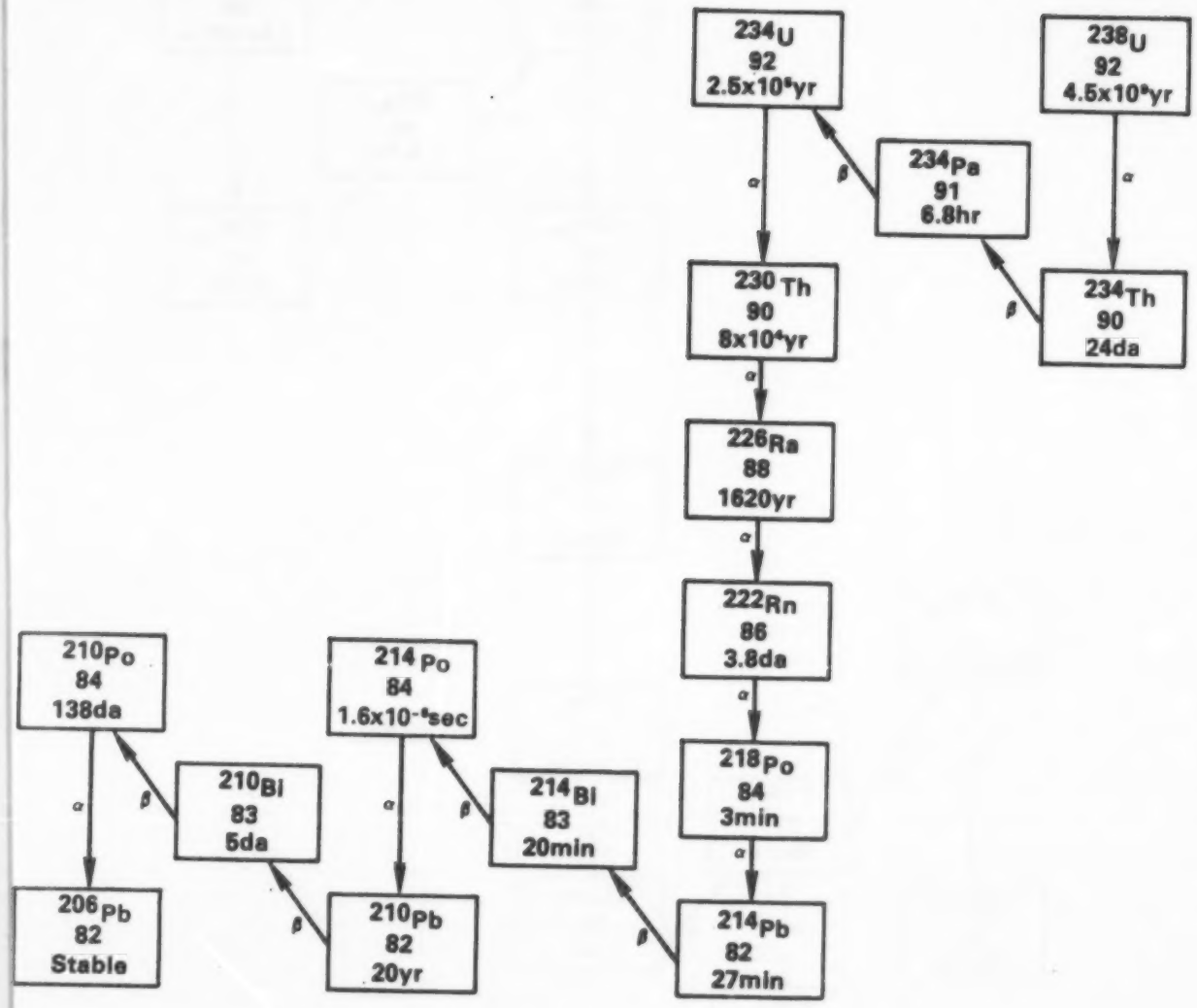
II NATURALLY OCCURRING RADIOACTIVE SERIES

III CONCENTRATIONS YIELDING 4 mrem/yr DOSE

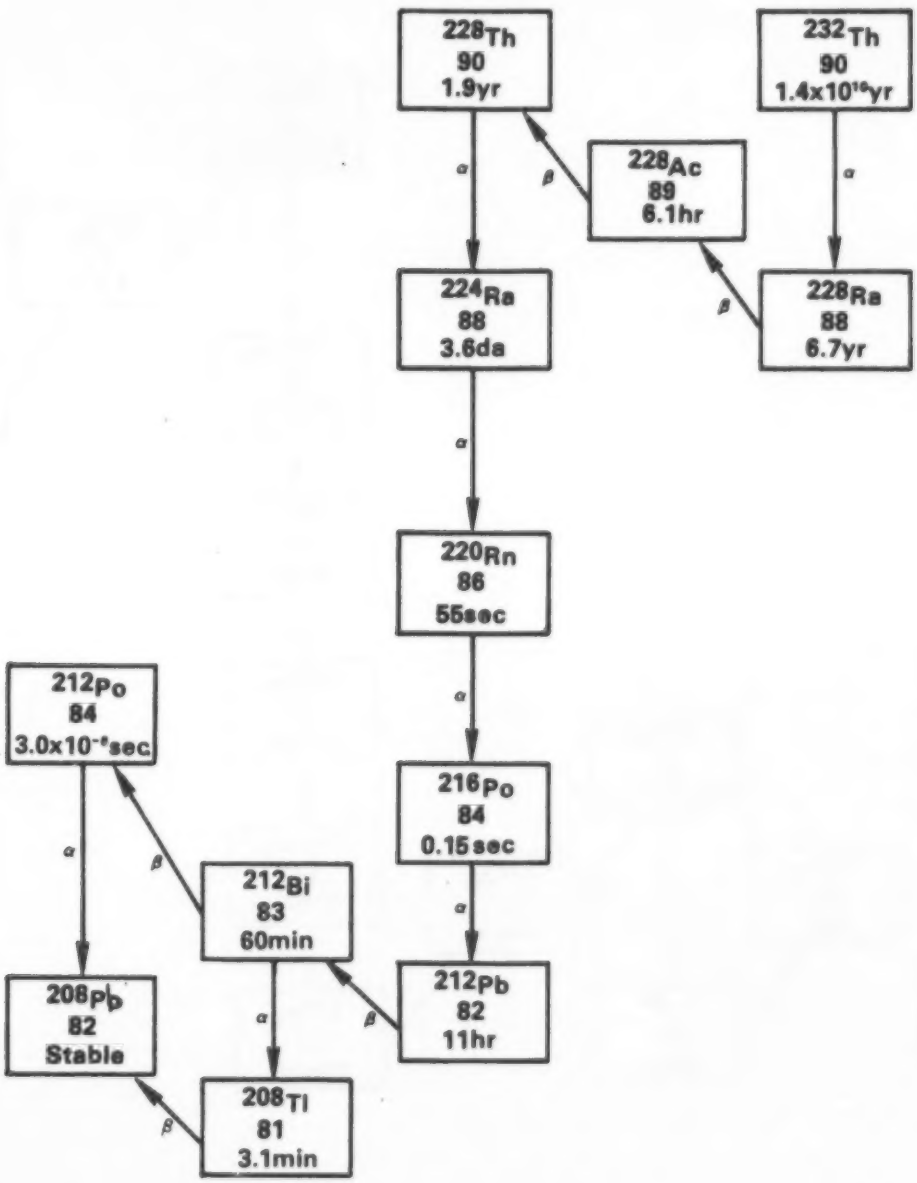
APPENDIX I
Chemical element symbols and atomic numbers

	Symbol	*Atomic Number*
Actinium	Ac	89
Aluminum	Al	13
Americium	Am	95
Antimony	Sb	51
Argon	Ar	18
Arsenic	As	33
Astatine	At	85
Barium	Ba	56
Berkelium	Bk	97
Beryllium	Be	4
Bismuth	Bi	83
Boron	B	5
Bromine	Br	35
Cadmium	Cd	48
Calcium	Ca	20
Californium	Cf	98
Carbon	C	6
Cerium	Ce	58
Cesium	Cs	55
Chlorine	Cl	17
Chromium	Cr	24
Cobalt	Co	27
Copper	Cu	29
Curium	Cm	96
Dysprosium	Dy	66
Einsteinium	Es	99
Erbium	Er	68
Europium	Eu	63
Fermium	Fm	100
Fluorine	F	9
Francium	Fr	87
Gadolinium	Gd	64
Gallium	Ga	31
Germanium	Ge	32
Gold	Au	79
Hafnium	Hf	72
Helium	He	2
Holmium	Ho	67
Hydrogen	H	1
Indium	In	49
Iodine	I	53
Iridium	Ir	77
Iron	Fe	26
Krypton	Kr	36
Lanthanium	La	57
Lawrencium	Lr	103
Lead	Pb	82
Lithium	Li	3
Lutetium	Lu	71
Magnesium	Mg	12
Manganese	Mn	25
Mendelevium	Md	101
Mercury	Hg	80
Molybdenum	Mo	42
Neodymium	Nd	60
Neon	Ne	10
Neptunium	Np	93
Nickel	Ni	28
Niobium	Nb	41
Nitrogen	N	7
Nobelium	No	102
Osmium	Os	76
Oxygen	O	8
Palladium	Pd	46
Phosphorus	P	15
Platinum	Pt	78
Plutonium	Pu	94
Polonium	Po	84
Potassium	K	19
Praseodymium	Pr	59
Promethium	Pm	61
Protactinium	Pa	91
Radium	Ra	88
Radon	Rn	86
Rhenium	Re	75
Rhodium	Rh	45
Rubidium	Rb	37
Rutheium	Ru	44
Samarium	Sm	62
Scandium	Sc	21
Selenium	Se	34
Silicon	Si	14
Silver	Ag	47
Sodium	Na	11
Strontium	Sr	38
Sulfur	S	16
Tantalum	Ta	73
Technetium	Tc	43
Tellurium	Te	52
Terbium	Tb	65
Thallium	Tl	81
Thorium	Th	90
Thulium	Tm	69
Tin	Sn	50
Titanium	Ti	22
Tungsten	W	74
Uranium	U	92
Vanadium	V	23
Xenon	Xe	54
Ytterbium	Yb	70
Yttrium	Y	39
Zinc	Zn	30
Zirconium	Zr	40

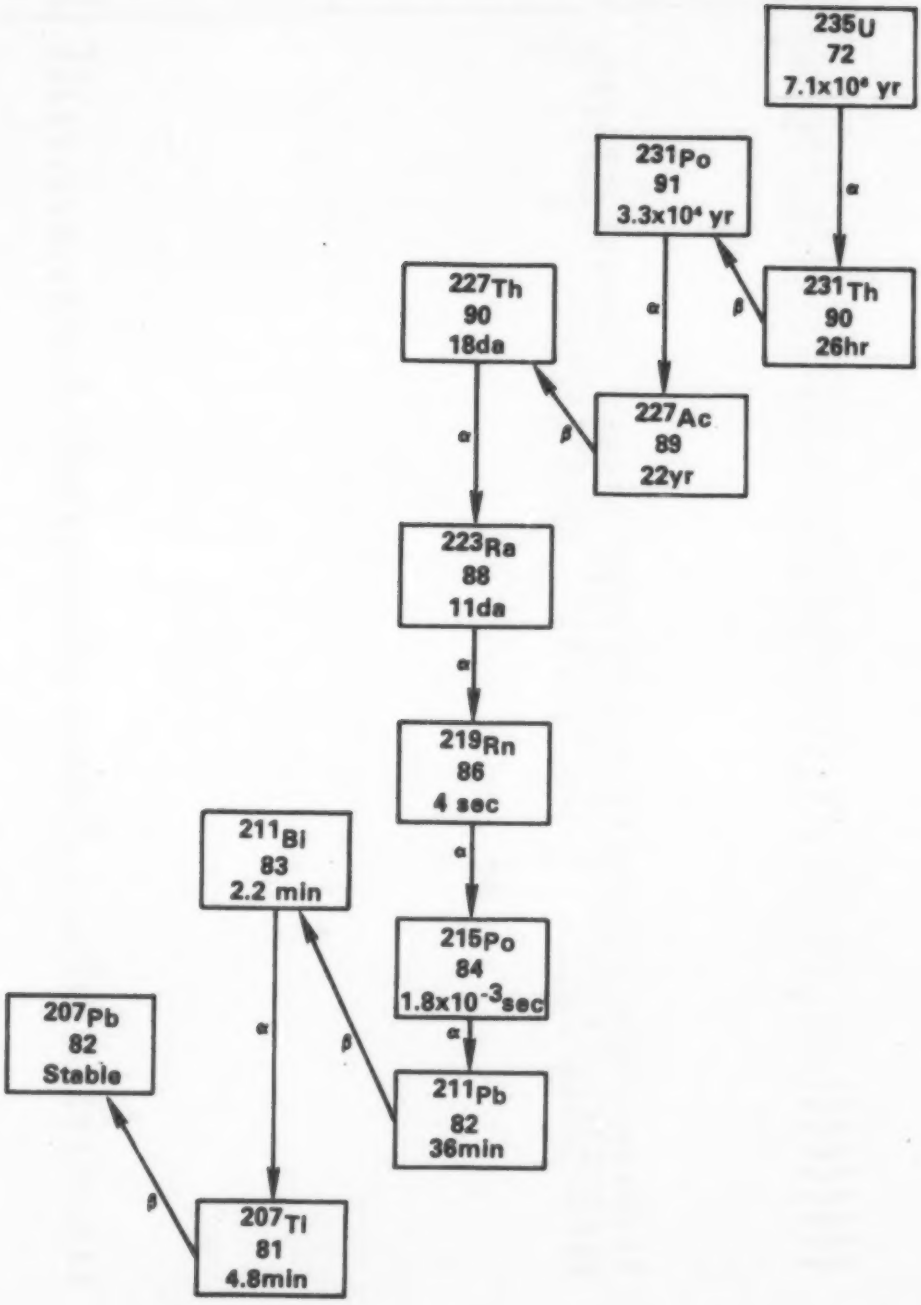
THE URANIUM SERIES



THE THORIUM SERIES



THE ACTINIUM SERIES



APPENDIX III

Annual Average Concentrations Yielding 4 Millirem per Year for a Two Liter Daily Intake, From National Interim Primary Drinking Water Regulations, EPA – 570/9 – 76 –003

Radionuclide	Critical Organ	C_4 (pCi/l)
Tritium	Total Body	20,000
$^{4}Be^{7}$	GI (LLI)	6,000
$^{6}C^{14}$	Fat	2,000
$^{11}Na^{22}$	Total Body	400
$^{11}Na^{24}$	GI (S)	600
$^{15}P^{32}$	Bone	30
$^{16}S^{35}$	Testis	500
$^{17}Cl^{36}$	Total Body	700
$^{19}K^{42}$	GI (S)	900
$^{20}Ca^{45}$	Bone	10
$^{20}Ca^{47}$	Bone	80
$^{21}Sc^{46}$	GI (LLI)	1,000
$^{21}Sc^{47}$	GI (LLI)	300
$^{21}Sc^{48}$	GI (LLI)	80
$^{23}V^{48}$	GI (LLI)	90
$^{24}Cr^{51}$	GI (LLI)	6,000
$^{25}Mn^{52}$	GI (LLI)	90
$^{25}Mn^{54}$	GI (LLI)	300
$^{26}Fe^{55}$	Spleen	2,000
$^{26}Fe^{59}$	GI (LLI)	200
$^{27}Co^{57}$	GI (LLI)	1,000
$^{27}Co^{58}$	GI (LLI)	300
$^{27}Co^{60}$	GI (LLI)	100
$^{28}Ni^{59}$	Bone	300
$^{28}Ni^{63}$	Bone	50
$^{30}Zn^{65}$	Liver	300
$^{32}Ge^{71}$	GI (LLI)	6,000
$^{33}As^{73}$	GI (LLI)	1,000
$^{33}As^{74}$	Gi (LLI)	100
$^{33}As^{76}$	GI (LLI)	60
$^{33}As^{77}$	GI (LLI)	200
$^{34}Se^{75}$	Kidney	900
$^{35}Br^{82}$	GI (LLI)	100
$^{37}Rb^{86}$	Total Body	600
$^{37}Rb^{87}$	Pancreas	300
$^{38}Sr^{85}$	GI (SI)	21,000
$^{38}Sr^{89}$	Bone	20
$^{38}Sr^{89}$	Bone Marrow (FRC)	80
$^{38}Sr^{90}$	Bone Marrow (FRC)	8
$^{39}Y^{90}$	GI (LLI)	60
$^{39}Y^{91}$	GI (LLI)	90
$^{40}Zr^{93}$	GI (LLI)	2,000
$^{40}Zr^{95}$	GI (LLI)	200
$^{41}Nb^{93m}$	GI (LLI)	1,000
$^{41}Nb^{95}$	GI (LLI)	300
$^{42}Mo^{99}$	Kidney	600
$^{43}Tc^{96}$	GI (LLI)	300
$^{43}Tc^{97m}$	GI (LLI)	1,000
$^{43}Tc^{97}$	GI (LLI)	6,000
$^{43}Tc^{99}$	GI (LLI)	900
$^{44}Ru^{97}$	GI (LLI)	1,000
$^{44}Ru^{103}$	GI (LLI)	200
$^{44}Ru^{106}$	GI (LLI)	30
$^{45}Rh^{105}$	GI (LLI)	300
$^{46}Pd^{103}$	GI (LLI)	900
$^{46}Pd^{109}$	GI (LLI)	300

$^{47}Ag^{105}$	GI (LLI)	300
$^{47}Ag^{110m}$	GI (LLI)	90
$^{47}Ag^{111}$	GI (LLI)	100
$^{48}Cd^{109}$	GI (LLI)	600
$^{48}Cd^{115m}$	GI (LLI)	90
$^{48}Cd^{115}$	GI (LLI)	90
$^{49}In^{115}$	GI (LLI)	300
$^{50}Sn^{113}$	GI (LLI)	300
$^{50}Sn^{125}$	GI (LLI)	60
$^{51}Sb^{122}$	GI (LLI)	90
$^{51}Sb^{124}$	GI (LLI)	60
$^{51}Sb^{125}$	GI (LLI)	300
$^{52}Te^{125m}$	Kidney	600
$^{52}Te^{127m}$	Kidney	200
$^{52}Te^{127}$	GI (LLI)	900
$^{52}Te^{129m}$	GI (LLI)	90
$^{52}Te^{129}$	GI (S)	2,000
$^{52}Te^{131m}$	GI (LLI)	200
$^{52}Te^{132}$	GI (LLI)	90
$^{53}I^{125}$	Thyroid	3
$^{53}I^{126}$	Thyroid	3
$^{53}I^{129}$	Thyroid	1
$^{53}I^{131}$	Thyroid	3
$^{55}Cs^{131}$	Total Body	20,000
$^{55}Cs^{134}$	Total Body	80
$^{55}Cs^{135}$	Total Body	900
$^{55}Cs^{136}$	Total Body	800
$^{55}Cs^{137}$	Total Body	200
$^{56}Ba^{131}$	GI (LLI)	600
$^{56}Ba^{140}$	GI (LLI)	90
$^{57}La^{140}$	GI (LLI)	60
$^{58}Ce^{141}$	GI (LLI)	300
$^{58}Ce^{143}$	GI (LLI)	100
$^{56}Pr^{143}$	GI (LLI)	100
$^{61}Pm^{149}$	GI (LLI)	100
$^{62}Sm^{151}$	GI (LLI)	1,000
$^{62}Sm^{153}$	GI (LLI)	200
$^{63}Eu^{152}$	GI (LLI)	60
$^{63}Eu^{154}$	GI (LLI)	200
$^{63}Eu^{155}$	GI (LLI)	600
$^{64}Gd^{153}$	GI (LLI)	600
$^{65}Tb^{160}$	GI (LLI)	100
$^{66}Dy^{166}$	GI (LLI)	100
$^{67}Ho^{166}$	GI (LLI)	90
$^{68}Er^{169}$	GI (LLI)	300
$^{69}Tm^{170}$	GI (LLI)	100
$^{69}Tm^{171}$	GI (LLI)	1,000
$^{70}Yb^{175}$	GI (LLI)	300
$^{71}Lu^{177}$	GI (LLI)	300
$^{72}Hf^{181}$	GI (LLI)	200
$^{73}Ta^{182}$	GI (LLI)	100
$^{74}W^{181}$	GI (LLI)	1,000
$^{74}W^{185}$	GI (LLI)	300
$^{75}Re^{183}$	GI (LLI)	2,000
$^{75}Re^{186}$	GI (LLI)	300
$^{75}Re^{187}$	GI (LLI)	9,000
$^{76}Os^{185}$	GI (LLI)	200
$^{76}Os^{191}$	GI (LLI)	600
$^{76}Os^{193}$	GI (LLI)	200
$^{77}Ir^{190}$	GI (LLI)	600

$^{77}Ir^{192}$	GI (LLI)	100
$^{78}Pt^{191}$	GI (LLI)	300
$^{78}Pt^{193m}$	GI (LLI)	3,000
$^{78}Pt^{193}$	Kidney	3,000
$^{78}Pt^{197}$	GI (LLI)	300
$^{79}Au^{196}$	GI (LLI)	600
$^{79}Au^{198}$	GI (LLI)	100
$^{80}Hg^{197}$	Kidney	900
$^{80}Hg^{203}$	Kidney	60
$^{81}Tl^{204}$	GI (LLI)	300
$^{82}Pb^{203}$	GI (LLI)	1,000
$^{83}Bi^{206}$	GI (LLI)	100
$^{83}Bi^{207}$	GI (LLI)	200
$^{91}Pa^{233}$	GI (LLI)	300

(Half-life less than 24 hours)

Radionuclide	*Critical Organ*	C_4 *(pCi/l)*
$^{9}F^{18}$	GI (SI)	2,000
$^{14}Si^{31}$	GI (S)	3,000
$^{17}Cl^{38}$	GI (S)	1,000
$^{19}K^{42}$	GI (S)	900
$^{25}Mn^{56}$	GI (LLI)	300
$^{27}Co^{58m}$	GI (LLI)	9,000
$^{28}Ni^{65}$	GI (LLI)	300
$^{29}Cu^{64}$	GI (LLI)	900
$^{30}Zn^{69m}$	GI (LLI)	200
$^{30}Zn^{69}$	GI (S)	6,000
$^{31}Ga^{72}$	GI (LLI)	100
$^{38}Sr^{85m}$	Total Body	900
$^{38}Sr^{91}$	GI (LLI)	200
$^{38}Sr^{92}$	GI (ULI)	200
$^{39}Y^{91m}$	GI (SI)	9,000
$^{39}Y^{92}$	GI (ULI)	200
$^{39}Y^{93}$	GI (LLI)	90
$^{40}Zr^{97}$	GI (LLI)	60
$^{41}Nb^{97}$	GI (ULI)	3,000
$^{43}Tc^{96m}$	GI (LLI)	30,000
$^{43}Tc^{99m}$	GI (ULI)	20,000
$^{44}Rh^{105}$	GI (ULI)	300
$^{45}Rh^{103m}$	GI (S)	30,000
$^{49}In^{113m}$	GI (ULI)	3,000
$^{49}In^{114m}$	GI (LLI)	60
$^{49}In^{115m}$	GI (ULI)	1,000
$^{53}I^{132}$	Thyroid	90
$^{53}I^{133}$	Thyroid	10
$^{53}I^{134}$	Thyroid	100
$^{53}I^{135}$	Thyroid	30
$^{55}Cs^{134m}$	GI (S)	20,000
$^{59}Pr^{142}$	GI (LLI)	90
$^{60}Nd^{149}$	GI (LLI)	900
$^{63}Eu^{152}$	GI (LLI)	200
$^{64}Gd^{159}$	GI (LLI)	200
$^{66}Dy^{165}$	GI (LLI)	1,000
$^{68}Er^{171}$	GI (ULI)	300
$^{74}W^{187}$	GI (LLI)	200
$^{75}Re^{188}$	GI (LLI)	200
$^{76}Os^{191m}$	GI (LLI)	9,000
$^{77}Ir^{194}$	GI (LLI)	90
$^{78}Pt^{197m}$	GI (ULI)	3,000
$^{81}Tl^{202}$	GI (LLI)	300